Using 3D direct manipulation for real-time structural design exploration

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I would like to thank Mom, Dad, my brother, my sister, my cat...

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Abstract

The impact of decisions on the design process is initially high and declines as the design matures. However, few computational tools are available for the early design phase; thus, an opportunity exists to create such tools. In the conventional workflow the architect uses geometric modelling tools and the engineer uses structural analysis tools in a sequential step. Parametric modeling tools are an improvement to this workflow as structural analysis plug-ins are available. This allows the architect to get structural feedback in an earlier stage, but still as a sequential step to the geometric modeling. The present work is a proposal to improve this workflow by integrating structural feedback with geometric modeling.

User interfaces of these tools needs to be needs to be interactive and agile enough to follow the designer's iterative workflow. Direct manipulation is a human-computer interaction style which enables interactive user interfaces. In this user interface style users can directly manipulate objects on the screen using real-world metaphors, which makes the users more engaged with their task and encouraged to further explorations. This is achieved through reducing the perceptual and cognitive resources required to understand and use the user interface. New technology opens up new possibilities to create new design tools that make use of very direct manipulation. These possibilities are further explored in this thesis through development of two such tools.

The first application that has been developed make use of the multi-touch of tablets. The multi-touch interface literally closed the gap between human and computer, which enables a very direct manipulation interaction for two dimensional (2D) user interfaces. The developed application is an interactive conceptual design tool with real-time structural feedback that allows the user to quickly input, and modify, structural models through the use of gestures. The second application extends these concepts and ideas into a three dimensional (3D) user interface by using a 3D input device named the Leap Motion Controller.

The present work purposes a way to integrate structural demands earlier in the design process by employing very direct manipulation user interfaces.

Keywords: Interactive structural analysis; Interactive structural form finding; 3D input device; Multi-touch user interfaces

Populärvetenskaplig sammanfattning

Det första skedet när ett byggnadsverk ska byggas är det konceptuella designskedet, det är här de första besluten om utformningen av byggnadsverket görs. I det traditionella arbetsflödet så utformas byggnadsverket först i ett ritprogram, sedan används ett annat datorverktyg för att verifiera att att det utformade byggnadsverket kan hantera de krafter som uppstår, t.ex. vind, egentyngd osv. Detta arbete är ett försök till att förbättra detta arbetsflöde genom att skapa nya verktyg som redan i ett konceptuellt designskede ger användaren en återkoppling till hur strukturen kan hantera de krafter som kommer att uppstå så att förbättringar på utformningen kan göras i ett tidigare skede.

För att skapa denna typen av verktyg så ställs höga krav på användargränssnitt, de behöver vara interaktiva och enkla att arbete med för att kunna följa designerns iterativa arbetsflöde. Direkt manipulation är en typ av användargränssnitt där användaren direkt kan manipulera objekt på skärmen. Denna typen av användargränssnitt skapar intuitiva gränssnitt som är enkla att förstå och som uppmanar användaren att experimentera och utforska möjligheter. Ny teknik skapar nya möjligheter att skapa nya designverktyg för konceptuell design som använder en sådan, väldigt direkt, gränssnittstil. Dessa nya möjligheter utforskas vidare i denna avhandling genom att utveckla två olika designverktyg.

Det första av dessa verktyg tillåter väldigt direkt manipulation för ett två-dimensionellt (2D) användargränssnitt genom att utnyttja moderna pekskärmar. I det utvecklade verktyget kan användaren enkelt mata in och manipulera modeller genom att använda pekskärmen. Användaren presenteras med resultat från strukturberäkningar i real-tid, vilket tillåter användaren att experimentera och utforska nya former. Det andra verktyget som har utvecklats vidareutvecklar dessa koncept och idéer till tredimensioner (3D) genom att använda en ny sorts 3D input enhet, som heter Leap Motion.

Resultatet från detta arbetet är ett förslag på hur verktyg för konceptuell design kan förbättras genom att interagera strukturella aspekter, detta sker med hjälp av väldigt direkta användargränssnitt.

Contents

Part I

Introduction and overview of the work

1 Introduction

1.1 THE STRUCTURAL DESIGN PROCESS

Before a new building or structure can be built it needs to be designed. This design phase, here termed structural design phase, is a very important step of the building process. The total cost for the structure, energy performance, structural performance etc. are largely dependent on the result of the structural design process.

The structural design process is never a straightforward procedure. Rather, solutions are reached through an iterative, and often chaotic process. The process can be divided in to the four following steps [1]:

1. Conceiving: The most important design step where the overall design concept and significant details are developed.
2. Modeling: Idealization and simplification of the structural design concept, building of models for structural analysis and calculation of forces.
3. Dimensioning: Deciding sectional dimensions of structural members depending on the choice of materials.
4. Detailing: Final details of nodes and connections including the creation of construction documents.

In reality there is not necessarily a clear distinction between the different design steps and the process can iteratively move forward and backwards until a solution is reached. In this thesis the term conceptual design refers to the first design step conceiving and the initial phase of the modeling step. In the initial design phase the design freedom is considerable. At the same time the impact on the final result of the of the decisions taken at this early stage are often crucial. In contrast, both the design knowledge and the availability of design tools increases as the design matures during the later design stages [2,3], see Figure 1.1 and Figure 1.2. The design knowledge comprises of all that is known of the final design, from color of

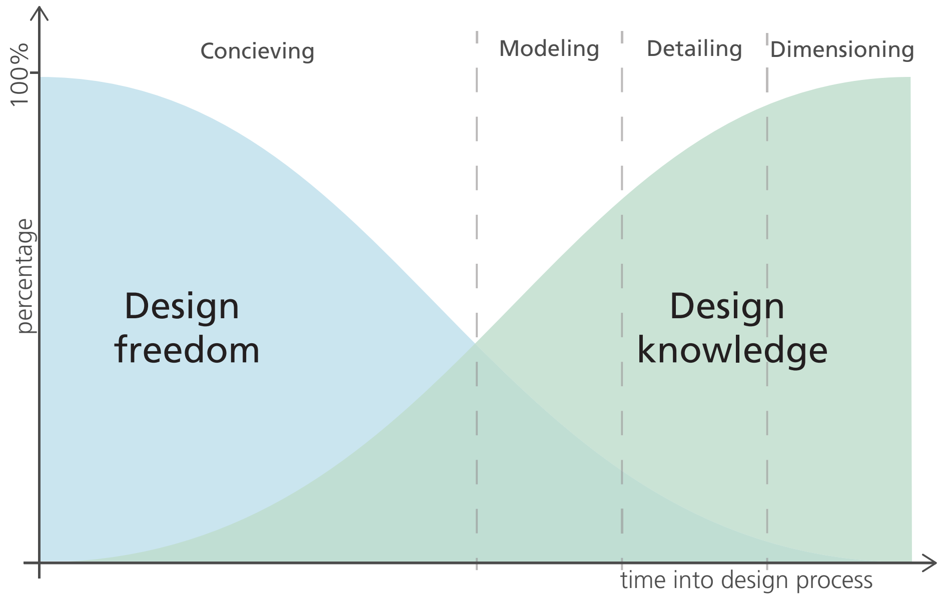

Figure 1.1: Structural design process [2]

the facade to dimensions of structural members. The lack of tools for the initial design phase combined with the high impact of decisions creates an opportunity to develop such tools. Tools that can support the designer to make well informed decisions in the conceptual design phase.

1.2 PROBLEM STATEMENT

Many different geometric modeling tools are today available for architects. These geometric modeling tools have, since their introduction in the 1980s, grown increasingly sophisticated. They have also, together with the widespread perception of the benefits of technological innovation, created a more intimate relationship between technology and design. This relationship has resulted in parametric design and scripting methods that can generate complex shapes and forms [4]. The distinct separation found in practice where architect's use geometric modeling tools and engineers use analysis tools further reinforces the architects role as form-giver and the engineer as form-verifier [5]. To move away from this separation, when the term designer is used in this thesis it represents either an engineer or an architect. Instead of the current practice, it would be beneficial if the engineer and architect would collaborate as designers in the structural design process. This would allow physical demands to work as an inspiration, rather then as a constraint of what is possible, to find new well performing geometric forms. Where physical demands can for example be: structural performance, construction costs, operational energy

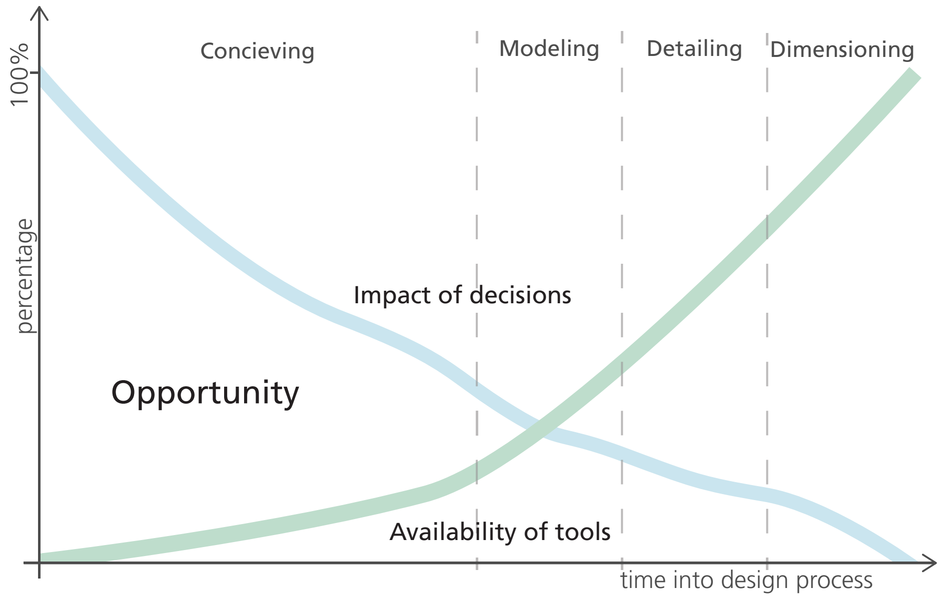

Figure 1.2: Impact of decisions and availability of tools in the design process [3]

needs, acoustics.

In the current practice the architect often conceives a design without involvement of the structural engineer. Hence, the importance of the conceptual design phase is often overlooked and structural aspects are often only considered in a late design stage [6]. A contributing factor to this is that very few computational tools are available for conceptual design.

The challenge when developing such computational tools lies within the fuzzy nature of the problem, knowledge and constraints of the problem are imprecise and incomplete [3].

Conventional advanced structural analysis software requires precise knowledge of the problem and is insufficiently agile to follow a designer's iterative workflow. Conventional structural analysis software is developed for use in the late design stage, when the major design decisions have been made, as a tool for the engineer to verify the form.

A subsequent problem with the traditional workflow, where the architect is the form-giver and the engineer is the from-verifier, can arise due to the availability of the a very detailed geometric model. It can be tempting for the engineer to directly perform a full analysis on the detailed geometry something which is possible with today's structural analysis software. If instead the engineer starts with a simple mathematical model and then gradually increases the complexity - known as hierarchical modeling, see Figure 1.3 – the risk of fatal mistakes is decreased [7].

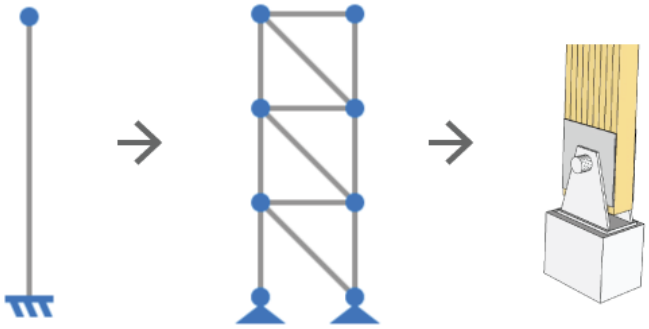

Figure 1.3: Hierarchical modeling

By starting with a simple mathematical model the engineer can focus on, and get a better understanding of, the overall structural behavior. Where the overall structural behavior is how stresses follow through the structure, what the magnitude of the stresses are in different structural members, etc. This information can be valuable when a more advanced mathematical model is used, to confirm the feasibility of the results. It has been shown that premature use of advanced structural analysis software negatively affects the conceptual understanding and the quality of the conceptual design [8].

In the present work, two similar computational conceptual design tools have been developed. The two applications make use of simple mathematical models, which enables structural modeling to be used earlier in the structural design process. The motivation for this is two-fold. It can give the designer valuable feedback on structural performance in the conceiving phase, when the impact of decision still is high. And it can also give the engineer valuable feedback on structural behavior before a more advanced model is used.

The type of design tool that is used to generate and represent ideas also affects the quality and quantity of early prototypes. It was shown in [9] that physical prototyping generated a higher quantity of prototypes, compared to using CAD or conventional sketching, under the same amount of time. The prototypes that were developed using physical prototyping were also perceived as more novel compared to the other prototypes. However, the prototypes that were perceived as more novel also tended to fare poorly on all other measureable qualities [9].

In the present work the prototypes are structural models. As computational models are used, a measurable performance can be computed and presented to the user in real-time. This can potentially can improve the quality of the structural models. The measureable performance and guidance in the present work put emphasis on the geometrical form of the structure as this has the greatest potential to improve the structural performance [10].

Figure 1.4: Pierre Luigi Nervi - Air hangar, built 1936

1.2.1 Examples of well-executed conceptual structural design

Structural demands can be integrated earlier in the design process by using them as inspiration of geometric forms instead of constraints of what is possible. Integrating structural demands earlier in the design process have the potential to reduce the amount of material needed, reduce environmental impact and lower costs for the project as a whole [2].

A good example of well-executed conceptual designs are the structures designed by the Italian architect-engineer Pierre Luigi Nervi, see example in Figure 1.4. Despite the complexity of his structures his designs were often selected because they were the cheapest to build [11], as less material was needed for his designs compared to his competitors. This type of complex concrete structure is unfeasible when labor costs are high, due to the extensive formwork required [12]. However, This is something which could of course change in the future with the emergence of robots and digital manufacturing [13].

"His buildings are most remarkable for the clarity of their engineering. The power and grace of these extraordinary shapes and patterns stems directly from their structural logic, and are inseparable from it" – Ada Louise about Pierre Luigi Nervi, 1960 [2]

The Shenzhen CITIC Financial Center, see Figure 1.5, is a more recent example of

Figure 1.5: Shenzen CITIC Financial Center, Lead Architectural Partner: Craig W. Hartman, Lead Structural Partner: Mark Sarkisian. Rendering © Skidmore, Owings & Merrill LLP, 2016

well-executed integrated conceptual design. The perimeter frames are inspired by research on optimal discrete truss geometries to minimize the material needed [14].

Designing Nervi's air hangar in 1936 required a very thorough understanding of structural mechanics. He was at the time the only one, or one of very few engineers that was capable of successfully designing such a structure. The CITIC Financial center was also designed by a team distinguished designers. The difference between the two examples are that the latter used computer computations in the design process.

1.2.2 Computational design tools

Computational design tools have the possibility make computer computations readily available in the design process, to help guide the designer towards well-performing solutions. Such tools have previously been developed and a review of existing tools and the methods that they implement are available in Chapter 3. These tools are developed to follow the designer's iterative workflow, which the conventional structural analysis software lacks.

Allowing these computational tools to follow the designer's iterative workflow puts high demand on the user interface of the tools. Most of the existing computational design tools are developed for mouse and keyboard input. In the present work alternative input devices are explored, which allows for a more direct input.

1.3 RESEARCH METHODOLOGY

1.3.1 Aim of research

The long term goal with this research is to improve the conceptual design phase by integrating structural demands early in the design process. An improved conceptual design phase has the potential to improve the quality of structures in the built environment. These qualities can for example be: structural performance, construction costs, operational energy needs, acoustics.

- To improve conceptual structural design by developing computational tools that bridge the gap between the design steps conceiving and modeling.
- To create intuitive conceptual structural design tools that allow the user to easily explore different design alternatives.
- To improve the human-computer interaction for such tools though use of new, novel user input devices.

1.3.2 Research questions

- How can the human-computer interaction be improved in computational conceptual structural design tools?
- Which computational methods can be used to improve the conceptual design phase?

1.3.3 Research approach and limitations

The present research is a multi-disciplinary work between structural mechanics, computer science and architecture. Methods from structural mechanics are used to provide the user with guidance and feedback. Developing user interfaces and employing programming techniques is a part of the computer science discipline. Studying conceptual design and finding geometrical forms are a part of architecture. The research is applied and any successful tools that this work results in could potentially be used in practice with few changes.

There are different research approaches to investigate how the conceptual structural design phase can be improved. In this work, it has only been investigated how new computational tools can improve the conceptual design phase. Project management, social aspects and culture is not considered in this work.

Many different computational methods exist that can be used for conceptual structural design. Some promising methods are presented in Chapter 4, a selection of these methods have been used in the present work.

Outline

Part I is an introduction to the research area and also literature review of previous work in this field. This part is similar to, but an extension of, the introductory sections in the appended papers. Chapter 1, is an introduction to the research area, and motivates why this work is important. Chapter 2 introduces human-computer interaction to the reader and introduces state of the art technology, such as new input devices. Chapter 3, presents computational methods that can be applied to conceptual design. Different optimization methods, especially the genetic algorithm, are thoroughly introduced; as these methods will be used in future work. Chapter 4 reviews existing conceptual structural design tools. In Chapter 5 the developed applications are presented, and the publications that this work has resulted in are presented in Chapter 6. Chapter 7 summarizes the present work and the intellectual contributions.

References

[1] Schlaich, M. (2006), *Challenges in Education–Conceptual and Structural Design*, in: *IABSE Symposium Report*, vol. 92, 20–26, International Association for Bridge and Structural Engineering.

[2] Mueller, C.T. (2014), *Computational Exploration of the Structural Design Space*, Ph.D. thesis.

Part II

Appended publications

Paper A

Optional text here.

Engineering and Computational Mechanics

A tablet computer application for conceptual design
Åkesson and Lindemann

ice | proceedings

Proceedings of the Institution of Civil Engineers

http://dx.doi.org/10.1680/eacm.14.00020
Paper 1400020
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A tablet computer application for conceptual design

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In the conceptual design phase, solutions are reached through an iterative, high-paced and often chaotic manner. Conventional advanced structural analysis software is often too advanced and insufficiently agile to follow this high-paced work pattern. Premature use of advanced structural analysis tools can negatively affect conceptual understanding and the quality of the conceptual design. The multi-touch interfaces of today's tablet computers give the user a strong feeling of direct manipulation of objects on the screen. This is interesting for structural mechanics applications, enabling direct manipulation of the structural model on the screen so as to have a better understanding and feeling of the structural behaviour. A tablet computer application for the conceptual design phase, which uses this type of direct manipulation interface, has been developed.

1. Introduction

> In practice a great many problems are solved by what is called judgment. The better a man understand how the stresses follow through a member or structure, the better his judgment will be. (Wolfe, 1921)

The earliest phase of the design process is referred to as the conceptual design stage. This stage is distinguished from the later design stages by more general questions and solutions (McNeill *et al*., 1998). The conceptual design stage starts with a general description of a problem and ends, after the creation and exploration of new ideas, with a general description of a solution (McNeill *et al*., 1998), in this case a structure. A structure is born during the conceptual design phase, and problems that arise in later design stages are often a result of careless conceptual design (Schlaich, 2006).

In the conceptual design phase, solutions are reached through an iterative, high-paced and often chaotic manner (Schlaich, 2006). Conventional advanced structural analysis software is often too advanced and insufficiently agile to follow such highly paced work patterns. It has been shown that premature use of advanced structural analysis tools can negatively affect the conceptual understanding and the quality of the conceptual design (Fröderberg and Crocetti, 2014).

The importance of the conceptual design stage is often overlooked and structural aspects are only considered in a late design stage (Schlaich, 2006). Structural engineers are in need of an improved conceptual design toolbox (Fröderberg and Crocetti, 2014), and new computer-aided tools could be a part of this toolbox.

New technology opens up new possibilities for computer-aided tools in the conceptual design phase. The iPhone, launched in 2007 (Kerris and Dowling, 2007), featured a revolutionary new input technology – the multi-touch interface. This is a touch screen that allows interaction with multiple fingers simultaneously, making it possible to interact using gestures, such as pinch to zoom or swipe to turn page.

The multi-touch interface has closed the gap between human and computer, giving the user a stronger feeling of directly manipulating objects on a screen (Sears *et al*., 1993). This makes it interesting for conceptual structural design applications, giving the user the ability to directly manipulate the model on the screen, which could result in a better understanding and feeling of structural behaviour. These possibilities are explored in this paper. A measurement of normalised redundancy has also been implemented; for further details see Tibert and Achi (2012).

2. Previous work

The emerging field of conceptual structural design computation seeks to close the gap between visualisation tools and computational analysis tools (Mueller, 2014). Numerous applications exist for conceptual structural design. Two different key features – guidance and feedback – can be identified for design tools that encourage integrated conceptual design (Mueller, 2014).

2.1 Guidance features

Applications with guidance features suggest new geometries to the user in order to improve the structural performance of the model (Mueller, 2014). These applications make use of different optimisation techniques to compute new geometries that are presented for the user. Two interesting similar applications that make use of topology optimisation are Forcepad (Lindemann *et al.*, 2004) and Topopt (Aage *et al.*, 2013); in these two applications, a two-dimensional geometry is modelled, a topology optimisation is then performed and the resulting optimised shape is visualised.

Another optimisation technique that can be used for conceptual structural design is the genetic algorithm (Goldberg, 1989). The two applications Structurefit (Mueller, 2014) and Evolutionary design tool (Von Buelow, 2008) make use of this technique to optimise the shape of truss networks. One of the strengths of using evolutionary computing in this context is that local optima can be determined and presented to the user as structurally well-performing design alternatives.

2.2 Feedback features

This type of application responds quickly to the user's input, ideally in real-time, to allow for an interactive user experience (Mueller, 2014). Numerous applications that implement real-time numerical analysis have been developed both for practice and for research. Two of the first applications to implement this approach were Pointsketch (Olsson, 2006), which was the inspiration for the present work, and an application called Arcade (Martini, 2006). These two applications make use of the finite-element method and bar elements, which the user can interact with using a mouse and keyboard user interface.

The commercial and widespread finite-element analysis (FEA) software SAP2000 introduced, in version 12, a 'model alive' feature that gives real-time feedback for forces and deformations in truss networks (Clune *et al.*, 2012). More recently, Autodesk – a software company known for visualisation tools – launched its new application ForceEffect both as a tablet and as a web application (Autodesk, 2015). The application is a tool for engineers to visualise and analyse truss networks, and also has support for visualising rigid body motions. According to Mueller (2014), 'the advantage of this class of tools over traditional structural analysis programs is the speed with which they convey results'.

3. FEA software in the conceptual design phase

Conventional FEA software is designed for later design stages, not the conceptual design phase. As the conceptual design phase has more general questions and solutions (McNeill *et al.*, 1998), software needs to be adapted accordingly. Often, conventional software is too complicated and time consuming to use, which does not integrate well with a designer's iterative workflow (Lindemann *et al.*, 2010).

4. Sketch-a-frame – a conceptual structural design tool

Sketch-a-frame is a finite-element iPad (Apple, 2014a) application for the conceptual design phase that makes use of beam elements. The application is free to download and available in the Appstore for iPad. The user interface is designed with the intention to be fast, intuitive and easy to understand. Instead of the conventional simulation sequence (see Figure 1), a more direct manipulation cycle is used, as shown in Figure 2.

The result is visualised when the model is considered complete; that is, if boundary conditions and one or more forces have been applied. When the model is complete it is determined if any rigid body motions are possible by calculating the determinant of the stiffness matrix; if the determinant is non-zero the model is stable. If the model is not stable and rigid body motions are possible an eigenvalue analysis is performed; the first modal shape is then visualised with an animation.

Computations are performed in real-time as changes are made to the geometry (e.g. when a node is moved the result is continuously updated and visualised; see Figure 2). Real-time visualisation encourages the user to experiment with the model in an explorative manner.

The application presents no numerical values on the geometry, forces or deformations. This is a design decision to encourage the user to focus on the general structural behaviour and not on the exact numerical results. This is not a tool to dimension structural members and therefore the material properties used are not relevant.

5. Theory and implementation

The application was developed using C++ and Objective-C. Finite-element computations are performed in C++ for performance reasons, using an external library called Newmat (Davies, 2014) for matrix operations. Newmat contains classes for common matrix and vector operations. The user interface was developed using Objective-C.

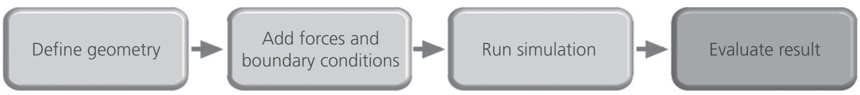


Figure 1. Conventional simulation sequence

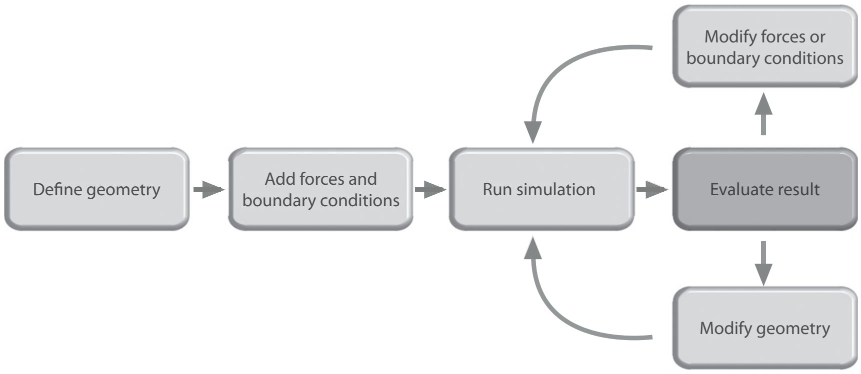


Figure 2. Direct manipulation cycle

5.1 Finite-element model

Beam elements (Bathe, 1996) are used for the computations. Every node has three degrees of freedom (DOFs) – vertical, horizontal and rotational – as shown in Figure 3.

5.2 Eigenvalue analysis

From the stiffness matrix **K** of a structure, a set of scalar stiffness values can be determined (Olsson and Thelin, 2003). Assume that a set of displacements $\boldsymbol{a}$ exists, which are proportional to a corresponding set of forces $\boldsymbol{f}$

$$\boldsymbol{f} = \lambda \boldsymbol{a}$$

This can be combined with a linear elastic finite-element formulation

$$\mathbf{K}\boldsymbol{a} = \boldsymbol{f} = \lambda \boldsymbol{a}$$

which can be rewritten as

$$(\mathbf{K} - \lambda \mathbf{I})\boldsymbol{a} = 0$$

This is a standard eigenproblem. The eigenvalues λ have dimensions of force/length, also called canonical stiffness values (Olsson, 2006). Every eigenvalue λ_i has a corresponding eigenvector $\boldsymbol{a}_i$, which describes a modal shape. Eigenvalues equal to zero means zero energy is required to form the corresponding modal shape (i.e. a rigid body motion). The eigenvectors are only defined within a scalar multiple. The eigenvector is normalised and multiplied by a positive and negative scalar, and the result is two different shapes. An animation of the rigid body motion can be achieved by interpolating between the two different shapes; this is implemented in Sketch-a-frame.

Figure 3. Beam element with six DOFs

5.3 Static redundancy factor

In Sketch-a-frame, normalised static redundancy factors are presented as a way to assess the redundancy of individual elements in the structure (Tibert and Achi, 2012). Only topology and geometry are studied in the analysis. Using the equilibrium matrix **H**, described in detail by Pellegrino and Calladine (1986), and the diagonal elements stiffness matrix $\boldsymbol{\Psi}$ yields (Tibert and Achi, 2012)

$$\boldsymbol{\Lambda} = \mathbf{I} - \mathbf{H}^{\mathrm{T}}(\mathbf{H}\Psi\mathbf{H}^{\mathrm{T}})^{-1}\mathbf{H}\Psi$$

The trace of the scaling matrix $\boldsymbol{\Lambda}$ is equal to the degree of static indeterminacy s

$$\mathrm{tr}(\boldsymbol{\Lambda}) = s$$

Thus, every diagonal element Λ_{ii} can be interpreted as element i's contribution to the structure's static indeterminacy, and is hence denoted the static redundancy factor. In Sketch-a-frame, the result is normalised and visualised using a colour scale (see Figure 4). Elements coloured blue cannot be removed without rendering the structure unstable, while elements coloured red are highly redundant. If there are any changes in the geometry (e.g. a bar is added or removed), the updated result is computed and visualised automatically.

In Example A of Figure 5, the vertical bar is 0% redundant as it is the only bar that provides vertical stiffness to the structure.

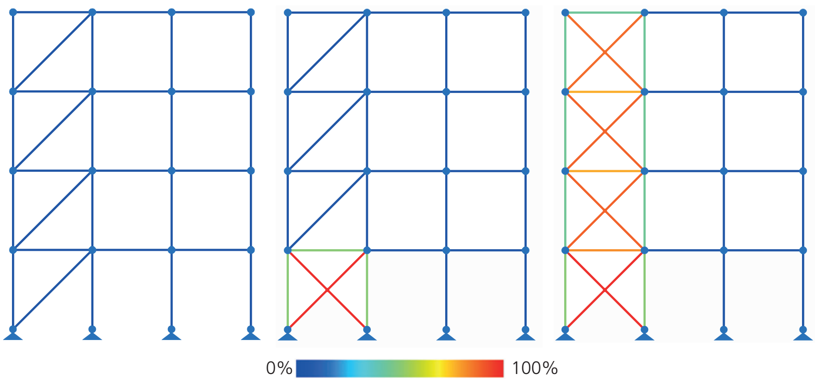


Figure 4. Normalised degree of redundancy

In Example B, the element coloured red is the most redundant element, but any element could be removed without rendering the structure unstable.

6. User interface

To make it easy for the tablet user to understand how different applications work it is important that there is consistency between them. Apple has guidelines for developers (Apple, 2014b). How an application works should not be based on the capabilities of the device, but on the way people think and work. The application should also be optimised for the device that it is running on. Aesthetic integrity is also of importance; it is not only about creating something beautiful, it is also how the design integrates with the functionality of the application.

Users enjoy direct manipulation on the screen – it keeps them engaged and gives a feeling of control (Apple, 2014b). Direct manipulation is a user interface style with continuous representation of objects of interest with rapid, reversible and incremental feedback (Shneiderman, 1982). Users can directly manipulate objects on the screen using real-world metaphors.

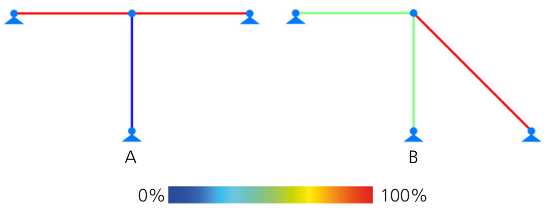


Figure 5. Normalised degree of redundancy, further examples

This user interface style creates intuitive user interfaces that work very well with the multi-touch screen (Sears *et al.*, 1993).

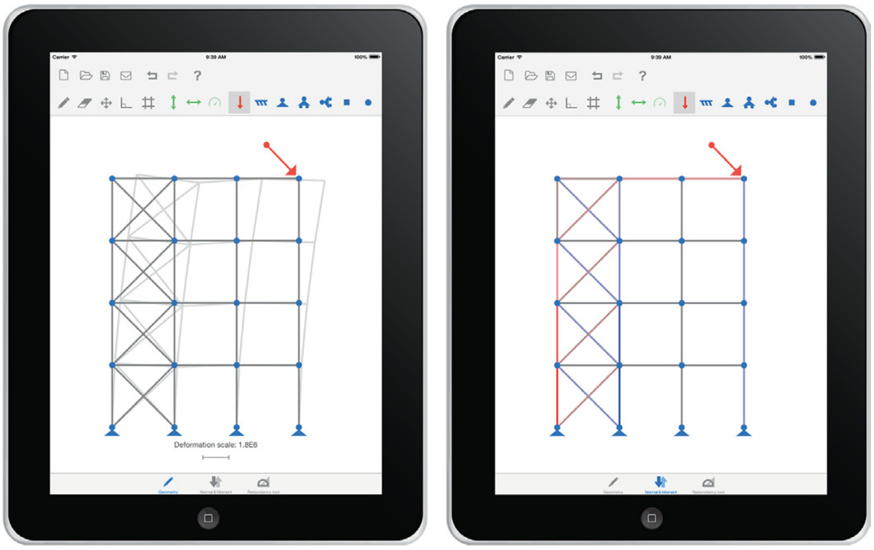
6.1 General layout of application

During the development process of the user interface, the quick and dirty evaluation paradigm (Rogers *et al.*, 2011) was used to quickly get feedback from users. In this paradigm, users are observed as they interact with the application with minimal control from the evaluators. Later in the development process, the usability testing evaluation paradigm (Rogers *et al.*, 2011) was used to review the performance of the interface and find further improvements. In the evaluation paradigm, users were given a task to perform as they were recorded using a camera, to be used for later assessments.

The goal of the user interface development was to create a simple to use and intuitive user interface. Feedback from the users guided the development to a user interface with three different pre-set visualisation modes (see Figure 6) available in a tab bar. The different modelling tools are always visible and accessible for the user in a toolbar. The three different visualisation modes are

- deformations
- normal force and moment
- normalised redundancy.

Figure 6. The three different visualisation modes



(a) (b)

Figure 7. (a) Deformations visualised; (b) normal force visualised

In the deformations mode, the deformed shape is visualised (see Figure 7(a)). In the normal force and moment mode, the normal force is visualised by colouring the elements red (for tension) and blue (for compression), as shown in Figure 7(b). If moment constraints exist, a moment envelope is visualised.

The application also has support for sharing the result. A pre-composed e-mail can be sent containing all the results in image format and a model file, which can be re-opened in the application.

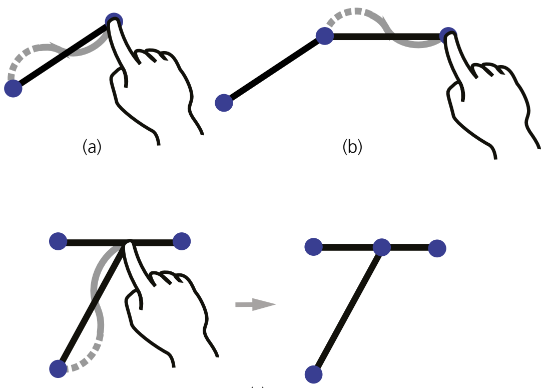
6.2 Geometric modelling

As shown in Figure 8, the modelling tools available to the user in the toolbar are

- pen – swipe to create elements and nodes
- eraser – swipe or tap to remove elements and nodes
- move – moves nodes; result is visualised in real-time during the movement
- undo and redo – changes can be undone and redone
- grid – a grid is shown that the tools snap against
- ortho – elements created are vertical or horizontal.

While using the pen tool and a swipe gesture is initiated, a node is created; when the gesture is released, an end node and an element between the nodes is created, as shown in Figure 9(a). When a swipe gesture is active, an element is visualised to the current position; if the current position is close to a node or a

Figure 8. Modelling tools



(a) (b) (c)

Figure 9. (a) Element created on release; (b) element connected from existing node; (c) new element connected to existing on release

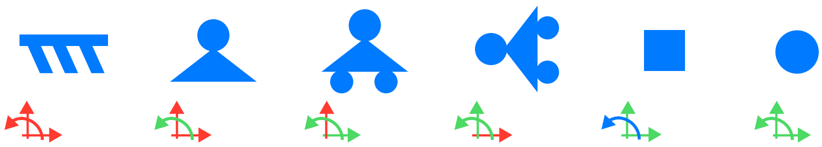


Figure 10. Boundary conditions: red arrows represent constrained DOFs, green arrows represent unconstrained DOFs and blue arrow can transfer bending moment between elements

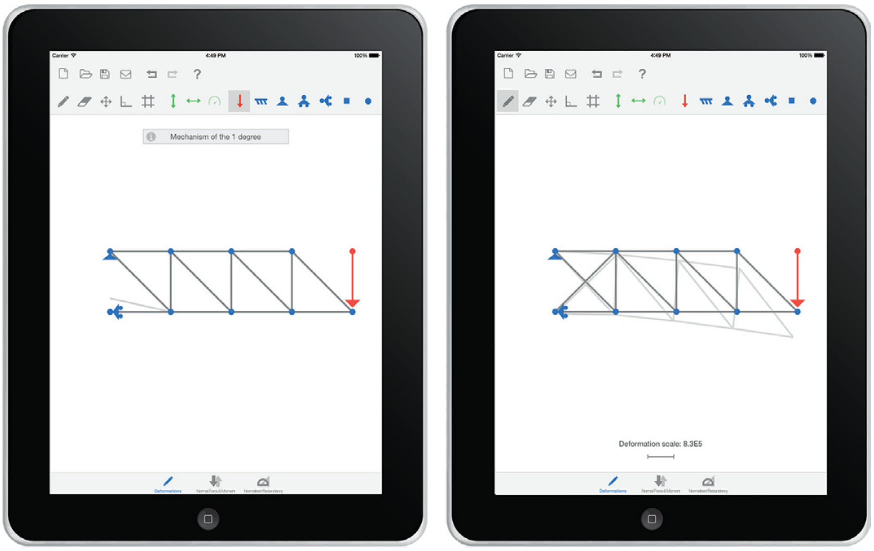


Figure 11. Assignment solved

line, the visualised element snaps to it. This also fits well in the direct manipulation of objects with continuous representation of objects of interest. This allows for a line or node to be the start or the end point of a new element (see Figures 9(b) and 9(c)).

6.3 Boundary conditions and forces

As beam elements are used, every node has three DOFs (i.e. vertical and horizontal translation and rotation), which can be constrained in different combinations. For simplicity, six of the most common combinations are implemented with symbols familiar to engineers (see Figure 10).

A force tool is also available. Tapping or swiping on nodes using this tool adds forces to the selected node. Forces can also be adjusted using the force tool and as the force is adjusted the result is visualised in real-time.

6.4 Scale

The difference in deformations between two models can be up to a factor of 10^9 times, depending on the stiffness of the model. To be able to visualise the deformation independently of the stiffness of the models, it needs to be scaled. However, constant rescaling removes some of the important feeling of directly manipulating the model. Rescaling when a swipe gesture is released was the best solution found; this retains the feeling of direct manipulation and allows the deformations to be visualised properly.

The current scale is presented to the user at the bottom of the screen together with a scale bar. The scale bar is always the same length as the largest deformation, and rescales when a swipe gesture is released. The same concept is used for visualising the moment envelope.

7. Application usage examples

7.1 Development of a roof truss structure in glulam

The application was used by two civil engineering students in their master thesis work to improve the market competiveness of glulam by developing a standardised concept for roof trusses for large open-space structures (Hedlund and Brorson, 2013). The following work process was used to find the most efficient truss designs.

- Inspiration and brainstorming – a large number of constructions was studied and evaluated. Inspiration was found from existing structures and literature, with the most successful constructions moving on to the next stage.
- Sketching – constructions were refined and improved.
- Rough design – cross-sectional forces were calculated using the software SAP2000 (CSI, 2015).
- Cost estimate based on cross-section and number of nodes.
- Selection based on comparison of stiffness, cost, number of nodes and installation.
- Final design, optimisation and cost estimation – roof trusses from the selection were further refined and a new cost estimation performed before the final design was chosen.

Sketch-a-frame was used in the first two stages in which the students brainstormed and explored different designs. The students preferred using the application over more advanced software in this conceptual design phase as a result of the speed of the interaction. The students also reported an increased initial understanding of the structural behaviour of the models.

7.2 Solving a course assignment

Some civil engineering students were given an assignment to solve. The task was to analyse a structure and determine if it was stable and, if not, give examples of improvements to make it stable. Most students solved the assignment by using Matlab and calculating the determinant of the stiffness matrix, but one of the students used Sketch-a-frame instead; the structure was quickly modelled and the result was immediately presented (see Figure 11). With animation of the rigid body motion, this student understood how the structure could be improved to make it stable and could quickly try different solutions.

8. Conclusions

The strength of tools with feedback features lies in the speed of the interaction and the fact that a freer exploration of structural forms is allowed. Sketch-a-frame further improves on the strengths of feedback feature tools as the speed of the interaction is improved with the multi-touch interface.

The multi-touch interface also gives a stronger feeling of directly manipulating the model on the screen, which encourages exploration and gives the user a feeling of control. With a higher speed of interaction, structural forms can be explored more freely compared with earlier mouse and keyboard feedback tools. However, some precision is lost with the multi-touch interface that can be a disadvantage for the geometric modelling of details. Another advantage of a tablet application is that it can easily be brought to meetings and used as a discussion tool, which can create a collaborative environment between participants.

The process of conceptual and structural design can be described by four steps – conceiving, modelling, dimensioning and detailing (Schlaich, 2006). In engineering, however, there is a lack of tools that support the first steps of conceiving and modelling. Sketch-a-frame provides such a tool. The development of the glulam roof structure is a good example of how Sketch-a-frame can be used to improve the conceptual and structural design process.

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Paper B

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Using 3D direct manipulation for real-time structural design exploration

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Abstract
The impact of decisions on the design process is initially high and declines as the design matures. However, few computational tools are available for the early design phase; thus, an opportunity exists to create such tools. New technology opens up new possibilities to create new and novel computational tools. In this work, an existing application is adapted for a new three-dimensional (3D) input device called the Leap Motion Controller. The controller allows the user to interact with 3D objects on a screen using his/her fingers and hands. The result of this work is a conceptual design application that enables very direct manipulation of 3D objects on the screen to a level that has not been achieved before for this type of application in 3D. An improved human-computer interaction can potentially improve the user's understanding of the structural behavior of a model, cognitive engagement in the design task, and encourage further design exploration. Three different cases are implemented to enable the user to explore different design options with emphasis on geometrical form, as this has the greatest potential to improve structural performance. These case studies demonstrate a new potential for building engineering intuition and improving design space exploration through very direct manipulation in 3D.

Keywords
Interactive structural analysis; Interactive structural form finding; 3D input device; Dynamic relaxation; Conceptual structural design

1 Introduction
The object of this paper is to demonstrate how an interactive three-dimensional (3D) environment can improve conceptual structural design. The goal is to improve the user's understanding of the structural behavior of a model and illustrate how geometrical modifications can change its structural performance.

1.1 Conceptual design tools
The earliest phase of the design process is referred to as the conceptual design phase. Decisions made in this phase have the highest impact of all the decisions made throughout the design process [1]; the impact of decisions then declines as the design matures. The importance of the conceptual design phase is often overlooked and structural aspects are often only considered at a late design stage [2]. A factor contributing to this situation is that very few computational tools are available for conceptual design. The challenge of developing such computational tools is the fuzzy nature of the problem: the knowledge and constraints of the problem are imprecise and incomplete [3]. Conventional advanced structural analysis software requires precise knowledge of the problem and is not agile enough to follow a designer's iterative workflow. It has been shown that premature use of such software can negatively affect the quality of the conceptual design [4]. Conventional structural analysis software has been developed for use in the late design stage, when the major design decisions have already been made, as a tool for the engineer to verify the form.

Many different geometric modeling tools are available for architects today. These geometric modeling tools have, since their introduction in the 1980s, grown increasingly sophisticated, and have, together with the widespread perception of the benefits of technological innovation, created a more intimate relationship between technology and design. This relationship has resulted in parametric design and scripting methods that can generate complex shapes and forms [5]. The distinct separation in design that means that architects use geometric modeling tools and engineers use analysis tools further reinforces the architects role as form-giver and the engineer as form-verifier [6]. To move away from this separation, the term "designer" is used in this paper to represent either an engineer or architect.

The type of design tool that is used to generate and represent ideas also affects the quality and quantity of early prototypes. It was shown in [7] that physical prototyping generates a higher quantity of prototypes within a limited amount of time. The developed prototypes were also perceived as more novel compared to the prototypes that where developed using computer aided design (CAD) or conventional sketches. However, the prototypes that were perceived as more novel tended to fare poorly with respect to all other measureable qualities [7]. As conceptual design is important and few conceptual design tools are available, an opportunity exists to improve the design process by developing such tools.

With new technology such as novel input devices and increased computational power comes new possibilities. The present work makes use of these possibilities to create a new way to interact with and create digital prototypes. The prototypes in this work are structural models. As a computational model is used, its measureable performance can be computed and presented in real-time to the user to potentially improve the quality of the structural models. The measureable performance and guidance in this work emphasizes the geometrical form of the structure, as this has the greatest potential to improve the structural performance. The result of the present work is a computational tool for conceptual structural design with a novel human-computer interaction interface.

1.2 Human-computer interaction

Direct manipulation is a style of human-computer interaction that has a continuous representation of the objects of interest with rapid, reversible, and incremental feedback [8]. Users can directly manipulate objects on the screen using real-world metaphors, which makes the users more engaged with their task and encouraged to explore further [9]. This is achieved by reducing the perceptual and cognitive resources required to understand and use the user interface [10].

The introduction of different input devices such as the mouse and joystick significantly improved the human-computer interaction of user interfaces, which adapted accordingly [10]. Later, when the touch screen was introduced, it had the advantage over these previous devices of a very direct method of inputting information [10]. It closed the gap between the human and computer, and the user could literally touch objects on the screen to manipulate them.

There is a wide repertoire of interaction techniques to create direct manipulation user interfaces for 3D applications using 2D input devices such as the mouse [11]. However, because these types of input devices have one degree of freedom less than the 3D user interface, there will always be a need for gestures or similar methods.

Computer games have seen an increase in the number of novel input devices along with new styles of games to address some of the limitations of conventional systems [12], e.g., the Wii Remote [13], Microsoft's Kinect for Xbox [14], and PlayStation Move [15]. These novel input devices move away from the conventional human-computer interaction to invoke an intuitive interaction that supports the natural human method of working. Games have for a long time been perceived as fun and engaging, and it has been investigated in many different disciplines whether gaming methods can improve human-computer interaction in order to create more effective, immersive, and engaging learning or training [12]. In computer aided design tools, the user experience has been compromised by the engineering design system's step-by-step evolution. The present work moves away from the step-by-step user interface to create an interactive, gaming-like experience using a novel 3D input device.

Although beyond the scope of this paper, the interest in and development of virtual reality glasses such as the Oculus Rift [16] and PlayStation's Project Morpheus [17] have recently increased. These types of virtual reality glasses have primarily been developed for games, but other fields have also shown interest, e.g., in [18], virtual reality is used to help students understand complex structural behavior.

2 Related work

Multiple software tools for conceptual structural design that deploy truss models have previously been developed. The first two such tools, PointSketch [19] and Arcade [20], were developed in parallel and released in 2006. In both software tools, the user can create a computational model using mouse and keyboard input. Forces can then be applied to the model and the results from the computations are visualized. The two software tools were both developed in academia, but industry has shown interest in the concept.

The commercial finite element software SAP2000 launched a "model alive" feature in 2012 that enables real-time feedback for deformations and forces [21]. The software was developed for use with truss-structures. However, geometrical modifications are made through text input. Autodesk launched a new application in 2011 named ForceEffect [22], which is available both as a tablet and web application. The application was developed for designers to analyze and visualize two-dimensional truss structures. The tablet application utilizes a direct manipulation user interface style, where the user can make changes to the model by directly touching the objects. A similar application that further developed the direct manipulation of the interaction is a tablet application named Sketch-a-Frame [23]. This application updates the visualizations of the computational result in real-time as the user makes changes to the geometry, creating a very direct manipulation. Another conceptual design tool that can generate structures through interactive optimization is called StructureFIT [24,25]. This software tool also has a direct manipulation mode, where the user can further explore a generated structure by moving nodes in real-time see how a relative performance index is updated.

Recently, an interactive physics engine was developed to create a user experience inspired by games for design and education [26]. The developed physics engine has been used to create an interactive game called Catastrophe, which aims to teach users which elements are critical to system stability through play.

A popular design tool in practice is the parametric modeler Grasshopper [27], which allows the user to manipulate parametric models through the use of sliders. This can be combined with Karamba [28], which is a structural analysis tool that can also give real-time feedback as to how the structural performance changes when the input parameters are altered. A tool that implements similar functions is Autodesk's Dynamo [29].

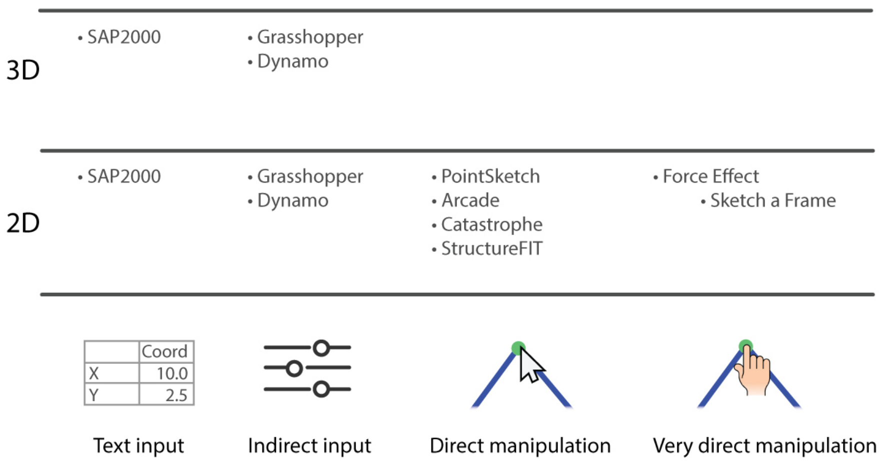

Figure 1: Summary of previous work

A summary of the evaluated conceptual design tools can be seen in Figure 1. The tools are grouped according to number of dimensions and how directly the manipulation can be experienced. Prior to the work presented here, no conceptual structural design tool has before been able to achieve very direct manipulation for 3D. A very direct manipulation user interface has so far only been achieved for 2D conceptual structural design tools. This is because of limitations of the traditional mouse and keyboard human-computer interaction with which the 3D applications were developed.

3 Methodology

The Leap Motion Controller [30] is a novel 3D input device. It can, with the use of infrared cameras, create a virtual model of a user's hands that are in the field of vision of the controller, as shown in Figure 2. This makes it possible to allow users to very directly manipulate representations of objects in 3D—which has the potential to improve the human-computer interaction of structural conceptual design applications. Improved interaction in such applications could potentially improve the user's understanding of the structural behavior of a model, cognitive engagement in the design task, and encourage further design exploration. The present work shows an implementation with a very direct manipulation for 3D that has not been achieved before for conceptual structural design tools.

Figure 2: Leap Motion Controller in use

3.1 Leap Motion Controller

A new 3D input device for computers was launched in July 2013 called the Leap Motion Controller [30]. By connecting the controller to a computer and placing it in front of the user, it can track the movement of fingers, hands, and tools with sub millimeter precision without any visible latency [30]. A software development kit (SDK) is available and supports most common programming languages [31], which can be used to implement support for the controller in existing applications.

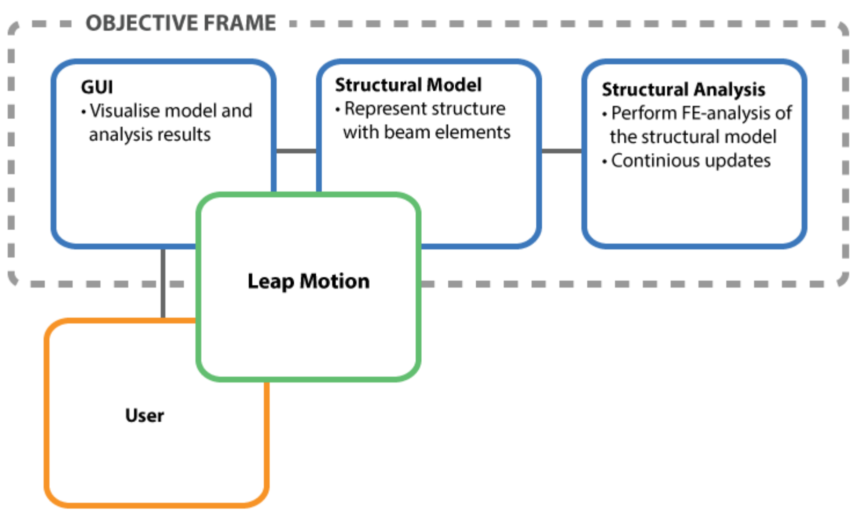

Figure 3: Conceptual diagram of how the Leap Motion Controller integrates into the existing conceptual design application ObjectiveFrame.

The SDK interprets the data from the controller's cameras and creates computational models of any hands or tools (e.g., a pen) that are in the field of vision of the controller. Using the SDK to integrate it with an application, the computational model can be accessed through the application programming interface (API), which has functions to return the positions and direction-vectors of hands, fingers, and tools in 3D. This can be used to build and visualize a virtual model of a hand or tool that can directly interact with the 3D objects on the screen. The SDK also has built-in support for gestures that can be used to call actions. This creates the potential to create very direct user interfaces for 3D, similar to the possibilities that the multi-touch user interface created for 2D.

However, new input devices require that software adapt accordingly in order to be successful [10]; thus, new 3D input devices are heavily dependent on software developers that can create new novel user interfaces.

3.2 Detailed implementation

The work in this paper builds on an existing application that was developed for conceptual structural design named ObjectiveFrame [32]. The application was developed in the C++ programming language and uses the FLTK toolkit [33] to create the graphical user interface (GUI) and the Newmat matrix library [34] to perform matrix operations.

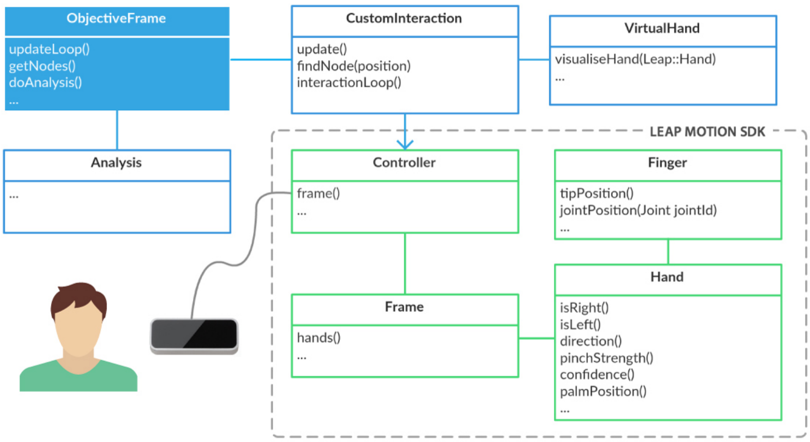

Figure 4: Diagram of how the Leap Motion SDK is integrated with the existing application.

When an instance of the class *Controller* is instantiated, the Leap Motion SDK creates a computational model of the objects in its vision field. The ObjectiveFrame application has an update cycle in which the objects of representation are continuously updated. The class *Controller* is queried at each update to obtain an updated *Frame* that contains information regarding the computational models.

Three different cases have been implemented in the existing application to demonstrate how the Leap Motion Controller can be used in the conceptual design phase.

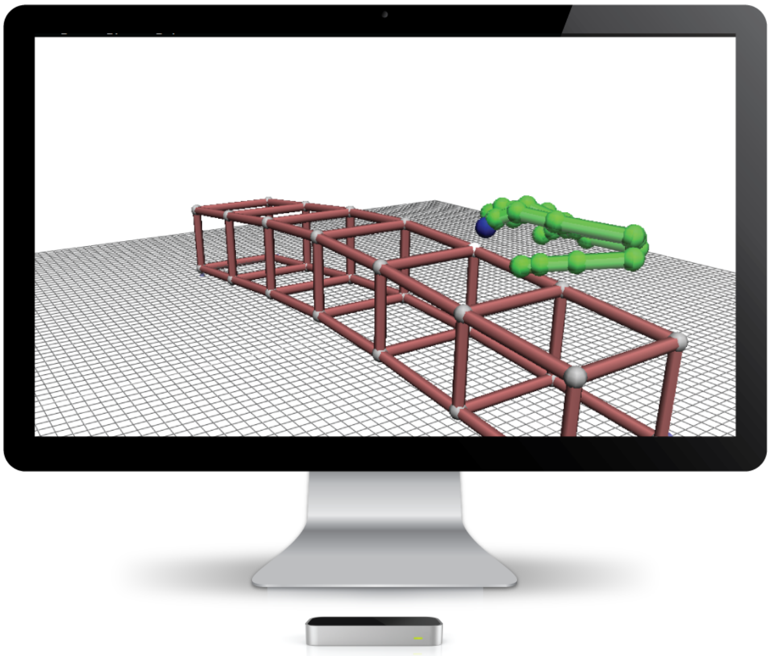

Figure 5: System setup with screenshot from the developed application.

3.3 Direct manipulation interaction model

The data from the Leap Motion SDK is used in the developed application to visualize a virtual model of the user’s right hand. The tip of the index finger on the virtual hand is colored blue, as shown in Figure 6—this fingertip is used to select nodes in the 3D space. When the index fingertip position is within a set distance of a node, the node is highlighted. The user can then perform a pinch gesture (see Figure 6) to interact with the highlighted node.

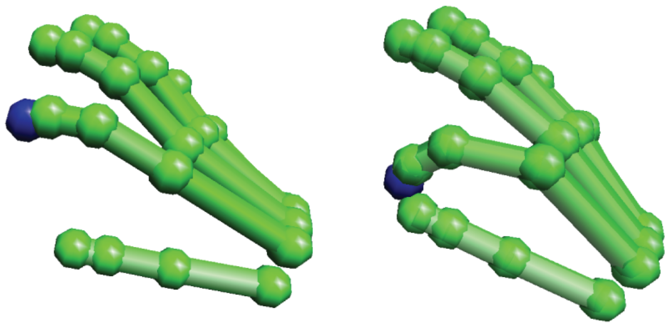

Figure 6: Pinch gesture visualized using the virtual hand model.

The right hand is used to interact with the structure while the left hand simultaneously controls the point of view, i.e., the location and angle at which the model is observed. Moving the palm closer or further away from the controller zooms out or in, respectively. This is a direct manipulation metaphor for pushing the model away. The palm position can also be used to rotate the point of view around the model by moving the palm sideways. The angle of the hand is used to control the angle at which the model is observed.

The position of the virtual hand is relative to the point of the view. Thus, when the user rotates the view, the virtual hand is rotated accordingly around the center of the view. This is in line with the metaphor in which the user reaches into the monitor to interact with the structural model. The Leap Motion SDK also has a confidence parameter. This parameter is lowered if the view is obstructed, e.g., if the left hand obstructs the view of the right hand. This is visualized using the opacity of the right hand to indicate the user that the view is obstructed.

4 Structural analysis for conceptual design

The *Analysis* block in Figure 4 shows the numerical analysis methods that have been implemented in the application to enable structural performance feedback and guidance in the application. In conceptual structural design, a simple mathematical model such as a truss or frame is advantageous for representing a structure [35]. The objective is a general understanding of the structural behavior and numerical precision is of less importance. In later design stages, the simple mathematical model can be substituted with a more advanced mathematical model for improved accuracy.

4.1 Structural analysis

To enable the application to visualize deformations and normalized structural performance, finite element analysis was implemented in the application. The application uses 3D beam finite elements that can be used to create frames or trusses to represent structures. Every beam element has two nodes—each has six degrees of freedom: three rotational and three translational ones [36]. The structural response is computed using

$$\boldsymbol{K}u = f$$

where K is the global stiffness matrix, u the displacement vector, and f the force vector. The compliance of the structure is the work (or strain energy) performed by the truss, and is the sum of the forces multiplied by the displacements:

$$W = \frac{1}{2} f^T u$$

This can be rewritten as

$$W = \frac{1}{2} u^T \boldsymbol{K} u$$

Ideally, the strain energy is a small number that corresponds to an efficient structure. To convey how geometrical modifications change the structural performance—the strain energy of the modified geometry is normalized in the developed application with the initial strain energy. The result is the normalized strain energy, a measure of how well the structure is performing.

4.2 Form finding

The process of designing form-found shapes is called form finding. Either physical models or numerical simulations can be used in this process, where the aim is to find the form for a structure under a load such that static equilibrium is satisfied. The static equilibrium corresponds to a structure that can support the applied load using only compression, and thus is a very efficient structure. For physical models, a hanging chain or cloth can be used the find the static equilibrium.

A number of different numerical methods exist to computationally find the form where static equilibrium is satisfied. The numerical method used in this work is dynamic relaxation, which is a method to solve a set of non-linear equations invented by Alistair Day in 1965 [37]. The method computes the movement of a structure over time to find equilibrium between the internal and external forces.

At each time step Δt, the internal forces for all elements are computed from nodal displacements u. The residual R can be computed using

$$R = f_{ext.} - f_{int.}$$

Using Newton's second law, the acceleration (derivative of the velocity with respect to time) can be computed as follows (at node i, in the x-direction, at time t)

$$R_{ix}^t = M_i \dot{v}_{ix}^t$$

where M_i is a lumped, fictitious mass at node i. To enforce boundary conditions, the residual is set to zero for the corresponding degrees of freedom. With a known time step, the velocity of node i in the x-direction can be computed using the finite difference method

$$v_{ix}^{t+\Delta t} = v_{ix}^{t-\Delta t/2} + \frac{\Delta t}{M_i} R_{ix}^{t}$$

With the velocity known, the updated geometry can now be updated using

$$x_i^{t+\Delta t} = x_i^{t} + \Delta t \cdot v_{ix}^{t-\Delta t/2}$$

After the geometry is updated, an iteration is complete and the computations start over, by again computing the residual. The geometry is modified at each iteration until equilibrium between the external and internal forces has been reached. Different types of damping such as kinetic or viscous damping can be used to get the solution to converge. In the present work, the velocities are set to zero in even intervals to obtain the desired dynamic behavior.

5 Case studies

The material parameters are not important in the following conceptual design case studies; however, they have a minor impact of the results and are therefore presented in Table 1.

Young’s modulus	$2{,}1 \cdot 10^{9}$
Area	$3{,}5 \cdot 10^{-3}$
Second moment of inertia	$5{,}3 \cdot 10^{-6}$

Table 1: Material properties (representing a steel tube) used in this study

5.1 Case I: Structural response

In this case study, a point load can be applied to a structure, and the resulting deformations are then visualized in real-time. When a pinch gesture is performed on a node, a point load is applied. Then, as the user moves the pinched fingers away from the node, the applied force changes direction and magnitude accordingly. Thus, the further the user moves the hand from the start position, the larger the magnitude of the applied force. The structural deformations are continuously computed and visualized for the user. As the pinch gesture is released, the applied force is removed and the structure is visualized in its undeformed shape.

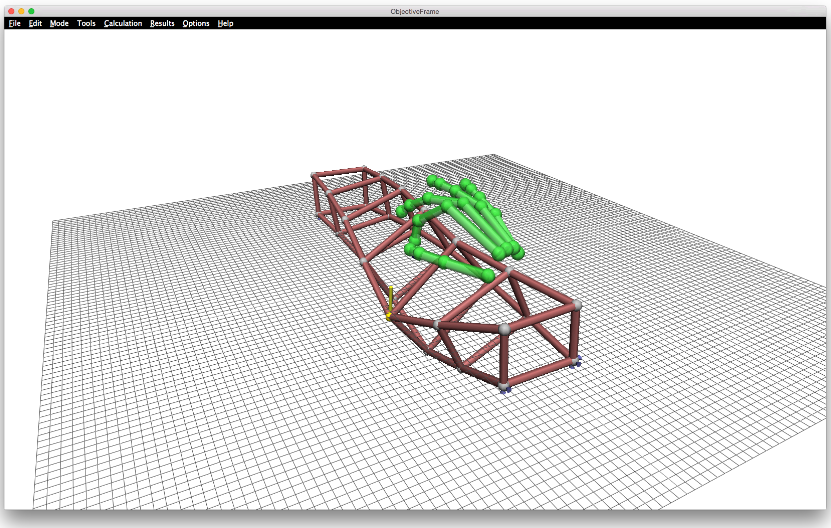

Figure 7: Structural response visualized in real-time

The scaling of the structural response is automatic and relative to the stiffness in the node where the force is applied. The applied force for node I in the x-direction is computed as follows:

$$f_{ix} = P_{currentx} - P_{startx}$$

where P_{startx} is the location of the index finger when the pinch gesture is performed and $P_{currentx}$ is the current position of the index finger.

5.2 Case II: Performance feedback

In this case, the user can move the nodes of a structural model using the pinch gesture. The strain energy of the structural model is continuously computed, normalized, and visualized on the screen for the user. The strain energy is normalized with the initial strain energy, thus the normalized strain energy is initially 1.0, where a lower value corresponds to a better performing structure.

An example of the design exploration process is shown in Figure 8; in this example, symmetry along the depth and width of the model is enforced. Thus, when a node is moved, three other nodes move to enforce symmetry. Enforcing symmetry makes the modeling process faster and different designs can easily be evaluated.

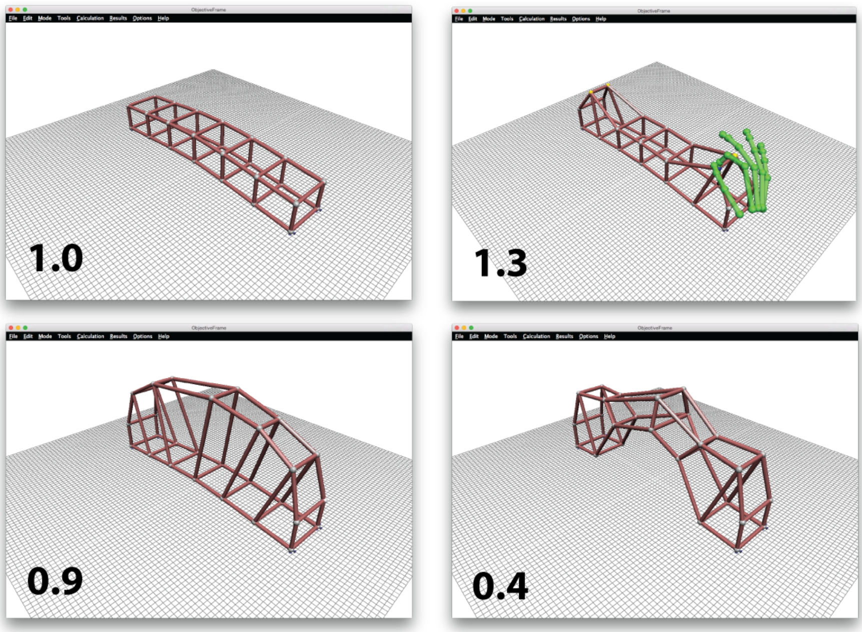

Figure 8: Design process with normalized strain energy

5.3 Case III: Dynamic relaxation

A dynamic relaxation method has also been implemented in the application. In this case, the geometry is computed and updated once every time the application refreshes. This results in an interactive application where the user can observe how the geometry is updated and modified until static equilibrium is reached.

In the following examples, a negative gravity load has been applied to the nodes. The user can then, by using the same interaction as described in Case I, apply a point load to any node. The benefit of using dynamic relaxation is that the geometry will start to converge towards the new static equilibrium even if the static equilibrium was not found for the parent load. This improves the interactivity of the application by following the direct manipulation guideline of continuously updating the object of interest. In Figure 9, an example is shown that corresponds to the physical prototype of a hanging chain.

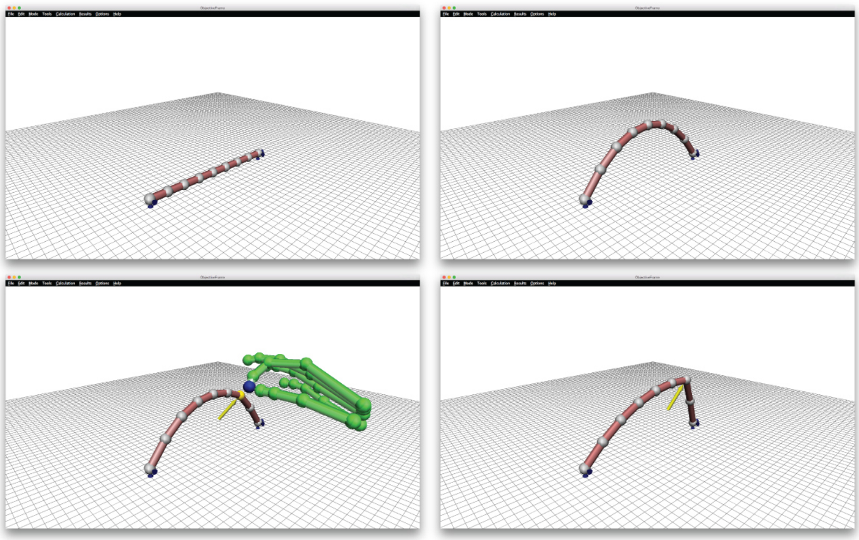

Figure 9: Educational example—the upper left image shows the initial geometry, and the upper right image shows the static equilibrium under a negative gravity load. In addition, the lower left image shows a point load being applied, and the lower right image shows the static equilibrium for a negative gravity load and point load.

As the designer applies a point load to the structure, the 3D dynamic response is interactively visualized. This can be used for educational purposes to improve the user's understanding of the structural behavior of the model.

In Figure 10, an example is shown where the dynamic relaxation is used to find the form of a structure. The point load can here be used to move away from the optimal solution [38] in order to find other interesting sub optimal solutions that might be more aesthetically attractive to the designer. The point load can also, for example, represent a supporting column or a hanging installation in the structure.

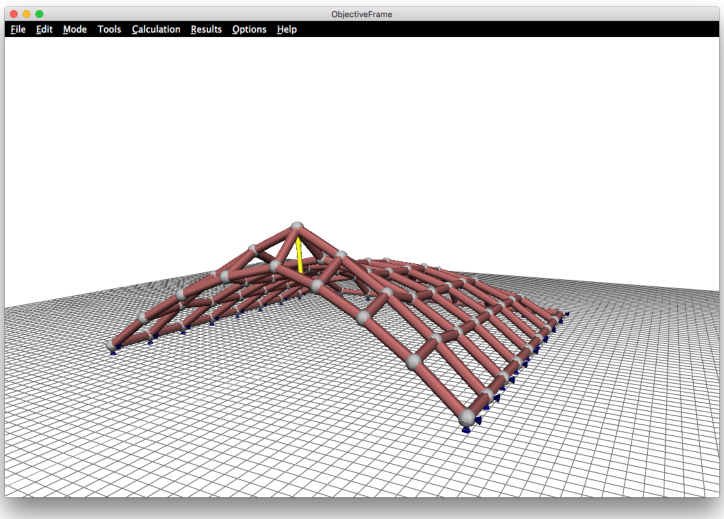

Figure 10: Example of a form-found structure using the developed application.

6 Discussion

This work shows that new 3D input devices have the potential to create very direct manipulation user interfaces for conceptual structural design, previously only achieved for 2D. The human-computer interaction in an existing application is improved, which improves the user's ability to explore different designs. The conceptual design environment is important, and it can have a big impact on the final design. This work shows an alternative user interface for the development of such tools, which in the future could potentially have a big impact on how we design structures.

The implemented methods aim to improve the designer's understanding of both the static and dynamic behavior. The implemented methods also allow the designer to navigate the design space and balance structural performance and aesthetics.

Hand gestures are used in the application to manipulate the location and angle from which the structure is observed. This could easily be implemented in existing CAD software to allow the user to more easily navigate the 3D space.

6.1 Summary of intellectual contributions

- This paper includes critical review of existing tools and techniques for design manipulation in conceptual CAD.
- It is the first to propose very direct manipulation as human-computer interaction mode for 3D structures, thanks to a new type of 3D input device such as the Leap Motion Controller
- It introduces an implemented design tool that allows users to interact with 3D structures through very direct manipulation.
- It demonstrates potential applications through three case studies.

6.2 Future work

The Leap Motion Controller's SDK supports virtual reality glasses such as the Oculus Rift. Combining the two can create a virtual reality in which the user can experience the structure in 3D, interact, and make changes to it using his/her hands.

This could potentially be developed in a game environment where the structure could be visualized in its intended context, i.e., a building site. A game engine could enable real-time renderings of the structure in its context. The designer would then be able to make manipulations, guided by performance feedback, to the rendered structure. This could improve the conceptual design process, and by doing so, have a big impact on the design process and final structure.

6.3 Concluding remarks

- This study responds to need for new, more intuitive, and natural interaction modes in computational design and analysis
- Very direct manipulation significantly improves existing direct manipulation paradigms prevalent in CAD.
- New technologies like the Leap Motion Controller open up unprecedented possibilities for engaging users in the exploration and design of 3D structures, leading to improved understanding of design options and performance in the built environment.

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